A Scalable Cyber-Physical System Data Acquisition Framework for the Smart Built Environment

Xinghua Gao[1]; Pardis Pishdad-Bozorgi, Ph.D.[2]; Dennis R. Shelden, Ph.D.[3]; and Shu Tang[4]

[1]School of Building Construction, Georgia Institute of Technology, 280 Ferst Dr., Atlanta, GA 30332. E-mail: gaoxh@gatech.edu
[2]School of Building Construction, Georgia Institute of Technology, 280 Ferst Dr., Atlanta, GA 30332. E-mail: pardis.pishdad@design.gatech.edu
[3]Digital Building Laboratory, School of Architecture, Georgia Institute of Technology, 245 4th St. NW, Atlanta, GA 30332. E-mail: dennis.shelden@design.gatech.edu
[4]Digital Building Laboratory, School of Architecture, Georgia Institute of Technology, 245 4th St. NW, Atlanta, GA 30332. E-mail: shutang@gatech.edu

ABSTRACT

With the networks of sophisticated sensors and devices, building systems have the potential to serve as the infrastructure that provides essential data for the Internet of things (IoT)-enabled smart city paradigm. However, current building systems lack inter-system connectivity or exposure to the larger networks of IoT devices. In this paper, we propose a scalable data acquisition framework for the smart built environment—smart buildings, smart communities, and smart cities—that enables the utilization of the data housed in separate building systems for innovative IoT use cases, by understanding IoT stakeholders' common data needs from buildings and identifying the overlaps between the data protocols used by different building systems. An architecture of IoT-enabled smart cities based on this data acquisition framework is also demonstrated.

INTRODUCTION

According to the United Nations, the world's urban population is projected to grow by 2.5 billion from 2014 to 2050, and will account for 66 percent of the total global population by then (UN DESA, 2015). The growing population in cities increases the demand for the fundamental needs of people living there, such as housing, utilities, medical care, welfare, education, and employment (Tascikaraoglu, 2018). To deal with challenges faced during the growth of cities, the concept of Smart City has been envisioned, which denotes "the effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens" (ISO/IEC_JTC_1, 2014). As the cells of smart cities, Smart Buildings integrate intelligence, enterprise, control, and materials and construction to meet the drivers for building progression: energy efficiency, longevity, comfort, and satisfaction (Buckman et al., 2014). In both the contexts of smart cities and smart buildings, the "smart" refers to the development, integration, and utilization of intelligent systems based on Information and Communication Technologies (ICT) and, more specifically, the Cyber-physical Systems (CPS) (NIST, 2017).

CPS refers to smart systems that include engineered interacting networks of physical and computational components (Group, 2016). It is also an umbrella term and concept that can represent many other words and phrases that describe similar or related intelligent systems, including the Internet of Things (IoT), machine-to-machine (M2M), industrial internet, digital city, etc. A CPS consists of the physical part – a device, a machine, or a building – and the digital or cyber part – the software system, communication network, and the data. The cyber part of CPS represents digitally the state of the physical part and impacts it by automated control or informing people of control actions. Researchers working in the CPS field are trying to connect the digital systems (the Internet, data, software applications, etc.) and the physical realm (machines, infrastructure, building components, etc.) to enable innovative applications and services.

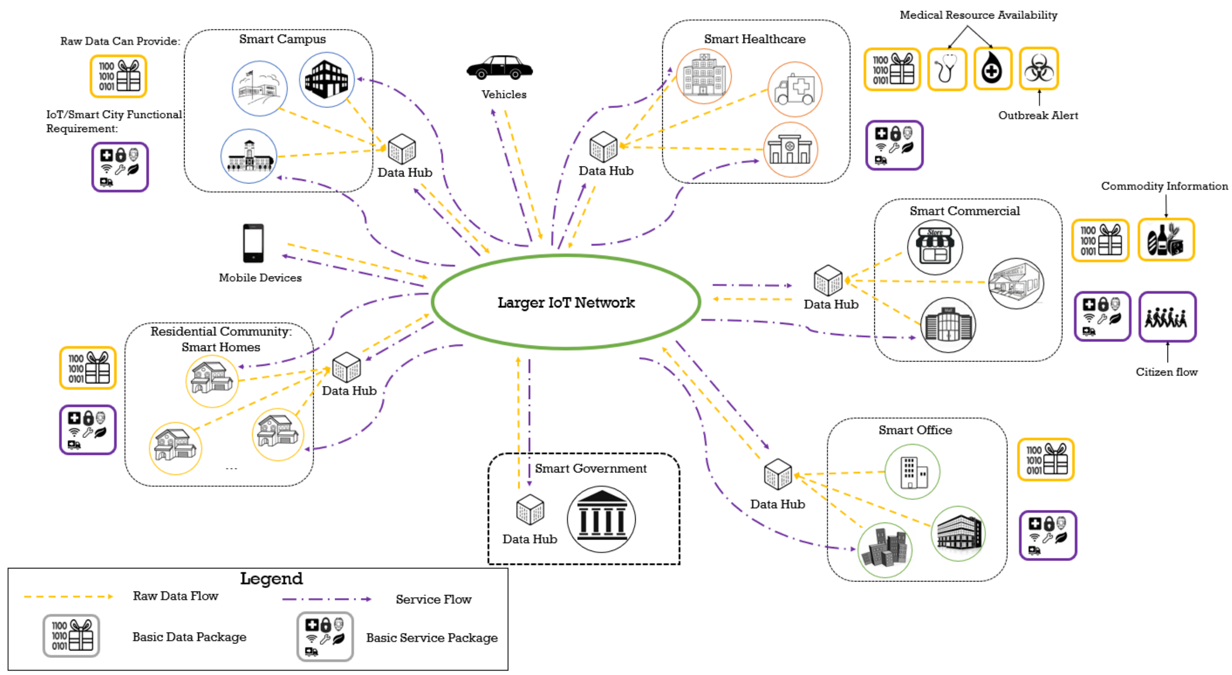

Figure 1. An architecture of the IoT-enabled Smart City – a network of smart facilities

The built environment is a critical component of the IoT-enabled Smart City paradigm. Buildings, along with infrastructures and vehicular/transit systems, comprise the platform into which ubiquitous computing and IoT systems are embedded. Buildings represent highly structured spatial environments – organizational systems of connecting spaces and components – that can provide a strong semantic overlay on the organization and interaction between IoT devices and their environments. Buildings provide intrinsic organizational information about the communities, businesses and operations of the people, equipment and systems they house. Buildings systems already incorporate proprietary networks of sophisticated sensors and devices in the form of energy systems, security systems, and emerging smart home devices, albeit with limited inter-system connectivity or exposure to the larger networks of IoT devices. These smart building sensor networks represent potential platforms for the deployment of more generalized IoT networks, and are sources of occupancy and space that can provide significantly enhanced value to new IoT systems (Gao et al., 2018).

In this paper, we propose a data acquisition framework for the smart built environment – Smart Buildings, Smart Communities, and Smart Cities – that enables the utilization of the data housed in separate building systems for innovative IoT use cases, by understanding IoT stakeholders' common data needs from buildings and identifying the overlaps between the data protocols used by different building systems. An architecture of IoT-enabled Smart Cities based on the proposed data acquisition framework and example use cases are presented in the next section. The proposed data acquisition framework and an experiment designed to prove its feasibility are described subsequently.

THE IOT-ENABLED SMART CITY – A NETWORK OF SMART BUILDINGS

In this section, a conceptual IoT-enabled Smart City architecture from the perspective of a smart building network is proposed and shown in Figure 1. It is our vision of future smart cities. The work done in this research is to establish the data infrastructure for this vision.

In the IoT-enabled Smart City we proposed, as Figure 1 shows, multiple smart buildings form a community. Multiple smart communities – such as residential community, campus, healthcare, commercial, office, and government – form a smart city. In the future, each facility will be "smart" enough to provide a certain amount of data to the IoT-enabled Smart City network in real-time. The data flow generated in each building is collected by the data hub of each community, and then connected to the city-level IoT network. The data contents can vary based on the facility type but some of them are universal. We name the data, which will be provided by all smart buildings "the basic data package". The basic data package provides the fundamental data for the Smart Buildings network and is the basis of innovative IoT-enabled Smart City applications.

Besides the basic data package, different data will be provided by certain types of facilities and we name them "extra data". For example, healthcare facilities can provide information pertaining to medical resource availabilities, such as the doctors' schedules and the blood bank inventory. They can also send outbreak alert to the smart city network if an infectious disease case is identified. Another example of extra data is that the supermarket in the smart commercial community can provide real-time commodity information to the smart city network so that citizens can locate the commodities they need. This is particularly crucial when natural disasters, such as the hurricane, tsunami, and sandstorm, are threatening the city and citizens are hoarding necessities.

The smart buildings in the proposed architecture not only provide data to the network but also require services from it. The service requirements may vary based on the facility types but there are some common services required by all. We name them "the basic service package". Some examples of the basic service package involve security, emergency assistance, data connection, operation and maintenance, etc. Besides the basic service package, different services may be requested by certain types of facilities and we name them "extra service". For example, a shopping mall may request real-time citizen flow information from the smart city network to predict the customer flow (Figure 1).

DATA ACQUISITION FRAMEWORK FOR THE SMART BUILT ENVIRONMENT

Currently, multiple building systems, such as the Building Automation System (BAS), the Building Energy Management Systems (BEMS), the Computerized Maintenance Management System (CMMS) and the security systems, are collecting a large amount of data through sophisticated sensors and emerging smart devices. However, the inter-system data interoperability is limited, and the data formats vary based on different vendors. Our hypothesis is that the evolving building systems already contain many valuable data for IoT-enabled Smart City innovations but are not effectively exploited because they are not connected, available to analysts and developers in a consumable way. We can establish the federated and integrated building data foundation and enable innovations in future Smart Cities by extracting relevant data from multiple building systems, storing them in cloud databases, and connecting these databases through customized Extensible Markup Language (XML) schemas, derived from the data mapping between different data standards.

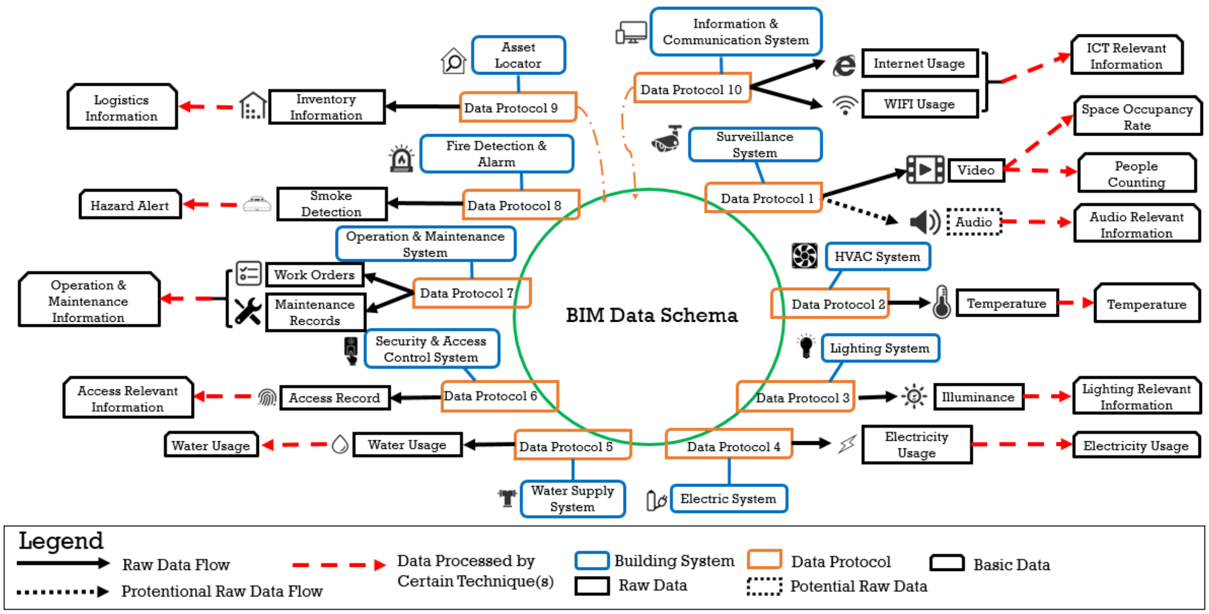

Figure 2. The basic data package generation

In this section, the conceptual framework to establish the basic data package is introduced first. Then, the methods of creating the data schemas for connecting separate building databases are illustrated. Finally, an experiment designed for demonstrating the proposed data acquisition framework is presented

The conceptual framework to establish the basic data package

Figure 2 illustrates the high-level framework to establish the basic data package. Separate building systems with different data protocols generate various types of raw data, such as the surveillance system generate videos, the Heating, Ventilation, and Air Conditioning (HVAC) system generates temperature information, the security and access control system generates access record, etc. The raw data can be processed by certain techniques – data mining, pattern recognition, Artificial Intelligence, etc. – to produce the “basic data”, such as space occupancy rate, people counting, and electricity usage.

Although a huge amount of building data is being generated every hour, the systems that generate these data are established based on various data standards and protocols. Currently, each type of building data is only used for a single purpose. For example, electricity consumption is for energy monitoring, temperature data is for HVAC system control, etc. The lack of a comprehensive usage of these building data is hindering the innovative applications of the IoT-enabled Smart Building/Smart City. A data framework that can provide integrated and comprehensive building data by connecting multiple databases, which are based on various standards and protocols, is the basis for realizing the innovative IoT-enabled Smart City use cases.

Building Information Models (BIM) (Eastman et al., 2011) offer a clear potential as the “digital twin” of the built environment – one that can provide significantly enhanced spatial context for distributed building automation and control systems, which can be regarded as IoT systems and CPS. A strategy for connecting the building automation and control/IoT data protocols with the BIM data schemas can provide a critical layer of spatial semantics to these IoT systems, such as device geo-positioning and metadata tagging, and enrich Smart Building/Smart City efforts while harmonizing these data sources with various data protocols. Extensive work is needed to enable the data connections between different building systems and to establish the proposed dataset. One of the prerequisites is a thorough investigation of the data standards and protocols of the IoT devices – sensors, cameras, actuators, etc. – and the BIM data schemas.

Industry Foundation Classes (IFC) specification is the leading neutral BIM data schema to describe, exchange and share building information (buildingSMART, 2017). Most of the BIM software applications support IFC. Currently, 653 entities (geometry, properties, and relationships of building components) can be defined in IFC and the capabilities of IFC as a data standard keep expanding (buildingSMART, 2018a). gbXML (gbXML Schema Inc., 2018) is another commonly used building data schema. CityGML is a city-level open data standard and exchange format to store digital 3D models of cities and landscapes (Open Geospatial Consortium, 2018a).

The method for establishing the linkage among different databases

The connections between the IoT data protocols with the BIM data schema can be established through identifying the overlaps between them and creating a federated data framework that enables the data collection, query, and exchange (Gao et al., 2018). The overlaps of the data protocol in each level – device level, building level (BIM), and city level – can be identified, such as device ID, space number, building name, and geolocation. These overlaps then can be used to establish the linkage among the databases of devices, buildings, and the city, thereby we can establish a federated dataset that provides real-time building data for IoT-enabled Smart City applications. In the visionary IoT-enabled Smart City, innovative CPS with appropriate permission will be able to query the real-time data generated by each IoT device. The proposed framework to establish the federated dataset is a critical effort to realize this vision.

The challenge of establishing the linkage among the databases lies in how to align the "common" data – such as device ID and building ID – in each database. For example, the device ID is "abcd123" in the device database but it may be "123-abcd" in the building database. To address this issue, we create XML schemas that enable automatically editing and concatenating the values of the key data fields, thus to align the common data.

An example experiment: connecting BACnet, IFC, and CityGML based databases

We are conducting an example experiment to demonstrate the proposed method for establishing the federated data framework and prove its feasibility. In this experiment, BACnet, IFC, and CityGML are adopted as the data protocol of device level, building level, and city level, respectively.

BACnet (A Data Communication Protocol for Building Automation and Control Networks) is the dominant protocol in the Building Automation Industry (bacnetwiki.com, 2017). The BAS used in the experiment – Johnson Controls' Metasys system – is based on BACnet and its devices are BACnet compatible (JohnsonControls, 2017).

Figure 3 shows the experiment framework. The data generated by the BAS's sensor network deployed in multiple campus buildings are collected and stored in a MySQL database. We did not use the database of Metasys directly due to lack of privilege and the need for making changes in the database without disturbing normal operations of the BAS. An open-source tool named BCVTB (Building Controls Virtual Test Bed) (Lawrence_Berkeley_National_Laboratory, 2017) is used to read the data generated by BACnet devices and write them to the database. This approach can extract any type of building data from BACnet supported device networks. In this experiment, we use the electricity consumption data as the device level data to connect with the IFC-based building database.

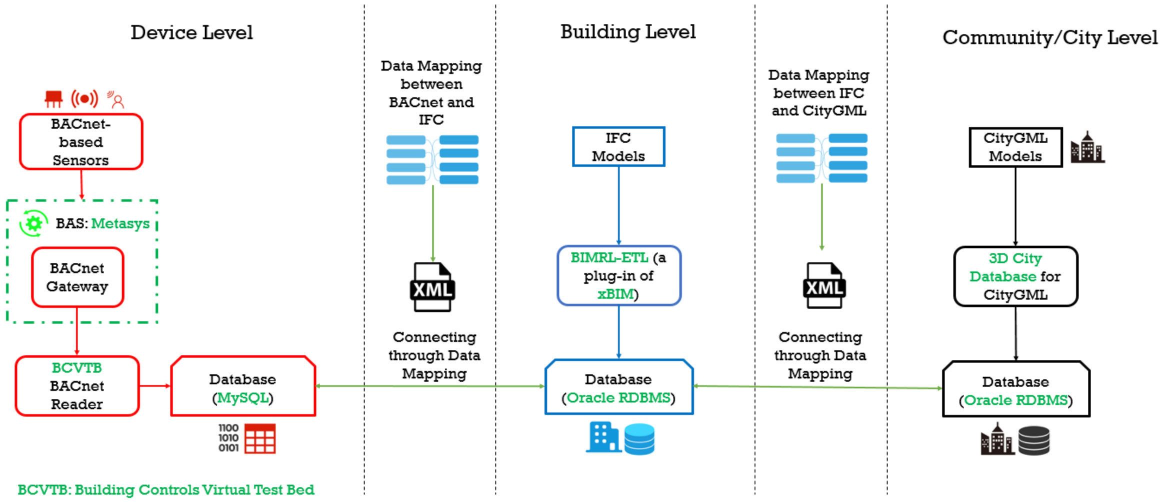

Figure 3. The experiment framework: connecting BACnet, IFC, and CityGML based databases

In the building level, to provide an efficient query-ability into BIM data, which is traditionally difficult and slow, two IFC models are transformed into a simplified RDBMS (Relational Database Management System) data format and stored in an Oracle Database Server (Oracle RDBMS). The tool we used in this step is called BIMRL-ETL (BIM Rule Language - Extract, Transform and Load) (Solihin, 2018), which is a plug-in of xBIM (Ward et al., 2018). The xBIM project aims to provide developers the codebase for innovative BIM applications.

In the community/city level, a CityGML city model is also transformed and stored in an Oracle Database Server. A tool named 3D City Database (3DCityDB) (Technische Universität München, 2018) is used to automate this process. The 3DCityDB is an open-source package consisting of a database schema and a set of software tools to import, manage, analyze, visualize, and export CityGML city models. “The database schema results from a mapping of the object-oriented data model of CityGML 2.0 to the relational structure of a spatially-enhanced relational database management system” (SRDBMS) (Technische Universität München, 2016).

To federate the data in each level’s database by using the common data fields, we have identified the overlaps (not exhaustively) between BACnet XML (BACnet XML Working Group, 2018) and ifcXML (IFC in the XML form) (buildingSMART, 2018b), and that between ifcXML and CityGML XML (Open Geospatial Consortium, 2018b). Based on the identified overlaps of these data schemas, we created XML files in MapForce (ALTOVA, 2018) to automatically editing and concatenating the values of the identified data fields, thus to align the common data in each database.

This in-progress experiment will prove the feasibility of the proposed scalable CPS data acquisition framework for the smart built environment, which involves – 1) studying different IoT data schemas, 2) identifying common data fields between these schemas and BIM data schemas, 3) creating the tools (may be as simple as an XML schema) to establish the linkage between databases, and thus 4) establishing the federated dataset for IoT-enabled Smart City applications. The proposed framework is scalable, which means if one type of building data can be extracted and stored in an SQL database, and this database can be linked to the building level database and then the community/city level database using the proposed methods, other types of data can also be processed by similar methods according to the framework, although the specific tools may be different in each case.

CONCLUSION

The built environment is a critical component of the IoT-enabled Smart City paradigm. Buildings, along with infrastructures and vehicular/transit systems, comprise the platform into which ubiquitous computing and IoT systems are embedded. Our hypothesis is that the evolving building systems already contain many valuable data for IoT-enabled Smart City innovations but not being used because they are not connected, available to analysts and developers in a consumable way. By extracting relevant data from multiple building systems, storing them in web-accessible databases, and connecting these databases through the data mapping between different data standards, we can establish the integrated building-IoT data foundation that enables innovations in future Smart Cities.

In this paper, we first propose a conceptual IoT-enabled Smart City architecture in the perspective of a smart building network, and highlight the concept of the basic facility data package – the common data set provided by smart buildings for IoT-enabled Smart City applications, such as people counting, energy consumption, access information, etc. Finally, we introduce the conceptual framework, the process, and the methods for establishing the basic data package, and present an ongoing experiment to demonstrate them.

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